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Experimental and numerical investigations on a combined biomass-solar thermal system

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Abstract

This paper presents investigations on a market available combined biomass-solar thermal system for heating and domestic hot water preparation designed for small residential applications. The system consists of a storage integrated pellet burner and a solar thermal loop delivering heat to the same storage over a heat exchanger. The investigations were performed in a project with the final goal of the optimization of the control strategy with an emphasis on the interaction of two subsystems – biomass and solar thermal.

The work carried out includes comprehensive laboratory measurements on system components, simulations based on the obtained experimental data and field tests on three installed systems. Measurements on the integrated pellet burner and the storage were performed under different steady-state and transient operating conditions and selected load profiles for both space heating and domestic hot water. The performance of the solar collectors was measured on an outdoor test rig according to the method with quasi-dynamic conditions described in EN12975:2006 chapter 6.3 [1].

The simulation was carried out in TRNSYS using previously validated models for all major system components [2, 3]. The experimental data from laboratory measurements were used to parameterize the simulation models using optimization based on an evolutionary algorithm (particle swarm optimization). The parameterized simulation models showed very good agreement with the experimental data. Hence, it was a reliable basis for the comparison with monitoring data and will provide a basis for future system optimization.

The four installation sights for field tests were chosen to include different types of buildings, thus providing information on system performance and behavior under different operating conditions. A comparison between the

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simulated and the measured performance of the system will be presented and discussed. In a next phase of the project, this comparison will help to identify potentials for further optimizations of the overall system with a focus on the system controller.

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Keywords: Solar collector; storage integrated biomass burner; combined solar thermal system

1. Introduction

Solar energy and biomass are two of the most promising primary energy sources in Europe. To further strengthen the market penetration of such energy systems two major tasks have to be solved. On the one hand side the investment costs of combined solar thermal and biomass systems tend to be relatively high since extra costs for the solar collectors arise. On the other hand side the system performance can be improved due to simpler installation and proper control strategies. This paper shows first results of a project to optimize a combined solar – biomass system. The inefficient installation is addressed by a highly integrated system, i.e. the pellet burner is directly integrated into the storage to minimize the use of material, thermal losses to the ambient and installation errors. In a next phase of the project the simulation model presented in this paper will be utilized to optimize the control set points and the control strategy to maximize the solar fraction thus minimizing the operational costs and to maximize the overall efficiency.

Nomenclature

A_{a}	Aperture area of the solar collector
b_0	Constant for the calculation of the incident angle modifier
c_1	Heat loss coefficient at $(\vartheta_{\mathrm{m}} - \vartheta_{\mathrm{a}}) = 0$
c_2	Temperature dependence of the heat loss coefficient
c_3	Wind speed dependence of the heat loss coefficient
c_5	Effective thermal capacity
c_6	Wind dependence in the zero loss efficiency
$C_{\mathrm{th,Bo}}$	Thermal capacity of the boiler associated only with the material of the combustion chamber without water
cp_{wat}	Heat capacity of water
E_{L}	Long wave irradiance $(\lambda > 3\mu\mathrm{m})$
F'	Collector efficiency factor
G_{b}	Direct solar irradiance (beam irradiance)
G_{b}	Diffuse solar irradiance
G^*	Global hemispherical solar irradiance
I_{solar}	Incident solar radiation in the solar collector plane

k_{eff}	Effective internal heat conduction of the thermal energy storage
$K_{\Theta\mathrm{b}}(\Theta)$	Incidence angle modifier for direct radiation
$K_{\Theta\mathrm{b}}(\Theta)$	Incidence angle modifier for diffuse radiation
L	Length of the solar collector
$\dot{m}_{\mathrm{Bo,fictive}}$	Mass flow rate of the fictive coupling
$\dot{m}_{\mathrm{coll}}$	Mass flow rate of the solar collector
$\dot{m}_{\mathrm{fuel}}$	Mass flow rate of fuel, i.e. wood pellets
$\dot{m}_{\mathrm{DHW}}$	Mass flow rate for domestic hot water
$\dot{m}_{\mathrm{space}}$	Mass flow rate for space heating
NHV_{wb}	Net heating value on a wet base
P_{aux}	Auxiliary power to operate the boiler
PER	Primary energy ratio
$\dot{Q}_{\mathrm{Bo}}$	Heat transfer rate of energy transferred from the boiler to the water
$\dot{Q}_{\mathrm{coll}}$	Heat transfer rate from the solar collector
$\dot{Q}_{\mathrm{DHW}}$	Heat transfer rate for domestic hot water
$\dot{Q}_{\mathrm{fuel}}$	Heat transfer rate from the fuel, i.e. wood pellets
$\dot{Q}_{\mathrm{losses}}$	Heat transfer rate of energy dissipated to the ambient and therefore lost for the process
$\dot{Q}_{\mathrm{losses,Bo}}$	Heat transfer rate of energy dissipated from the boiler including exhaust gas losses and thermal losses to the ambient and therefore lost for the process
$\dot{Q}_{\mathrm{losses,TES}}$	Heat transfer rate of thermal energy dissipated from the thermal energy storage to the ambient and therefore lost for the process
Q_{stored}	Energy stored in the thermal energy storage
$\dot{Q}_{\mathrm{space}}$	Heat transfer rate for space heating
$\dot{Q}_{\mathrm{useful}}$	Heat transfer rate of useful energy
SF	Solar fraction
SPF_{th}	Seasonal performance factor
T_{a}	Ambient or surrounding air temperature
$T_{\mathrm{dp,in}}$	Inlet temperature of double port for the fictive coupling
$T_{\mathrm{dp,out}}$	Outlet temperature of double port for the fictive coupling
$T_{\mathrm{f,coll}}$	Flow temperature of the solar collector
$T_{\mathrm{f,DHW}}$	Flow temperature for domestic hot water

$T_{\mathrm{f,space}}$	Flow temperature for space heating
$T_{r,\mathrm{coll}}$	Return temperature of the solar collector
$T_{r,\mathrm{DHW}}$	Return temperature for domestic hot water
$T_{\mathrm{r,space}}$	Return temperature for space heating
u	Surrounding air speed
UA_{bottom}	Heat loss coefficient of the bottom of the storage
$UA_{1\ldots4}$	Heat loss coefficient of the four different zones of the thermal energy storage
UA_{top}	Heat loss coefficient of the top of the thermal energy storage
UA_{solar}	Heat transfer coefficient of the storage integrated solar heat exchanger
V_{HTF}	Volume quantity of heat transfer fluid
$\dot{V}_{\mathrm{HTF,nom}}$	Nominal volume flow rate through the solar collector
W	Width of the solar collector
λ	Air ratio for the combustion process
σ	Stefan-Boltzmann constant
Θ	Angle of incidence
ϑ_{a}	Ambient or surrounding air temperature
ϑ_{m}	Mean temperature of heat transfer fluid
$(\tau\alpha)_{en}$	Effective transmittance-absorptance product for direct solar radiation at normal incidence

2. Experimental tests

2.1. Solar collector

All tested and monitored plants are equipped with the Solarfocus GmbH solar collector sunny 28. The main data from the manufacturer is given in table 1.

Table 1. Parameters of the solar collector sunny 28 from Solarfocus GmbH

Parameter	Value	Unit	Description
L	2.4	m	Length of the collector
W	1.155	m	Width of the collector
A_a	2.5	m^2	Aperture area of the collector
V_HTF	1.3	litre	Volume quantity of heat transfer fluid
$\dot{V}_\mathrm{HTF,nom}$	20 - 70	litre/(m^2h)	Nominal volume flow rate through the collector

The solar collector was tested on an approved and accredited outdoor test rig under quasi-dynamic conditions (QD-method) according to EN12975:2006 chapter 6.3 [1]. The following equation holds for the QD-method to model the solar collector:

$$\frac{\dot{Q}_\mathrm{coll}}{A_\mathrm{a}} = F' \cdot (\tau\alpha)_\mathrm{en}\, K_{\Theta\mathrm{b}}(\Theta) G_\mathrm{b} + F' \cdot (\tau\alpha)_\mathrm{en}\, K_{\Theta\mathrm{d}} G_\mathrm{d} - c_6 u G^* - c_1(\vartheta_\mathrm{m} - \vartheta_\mathrm{a}) - c_2(\vartheta_\mathrm{m} - \vartheta_\mathrm{a})^2 - c_3 u(\vartheta_\mathrm{m} - \vartheta_\mathrm{a}) + c_4(E_\mathrm{L} - \sigma T_\mathrm{a}^4) - c_5 \frac{d\vartheta_\mathrm{m}}{dt} \tag{1}$$

With the following equation valid for flat plate collectors only:

$$K_{\Theta\mathrm{b}}(\Theta) = 1 - b_0\left(\left(\frac{1}{\cos(\Theta)}\right) - 1\right) \tag{2}$$

The parameters in eq. (1) and eq. (2) are determined with the multi linear regression method (MLR-method). Table 2 shows the identified parameters for the collector model and fig. 1 shows the collector efficiency curve.

Table 2. Parameters determined for the solar collector

Parameter	Value	Unit
$F' \cdot (\tau\alpha)_\mathrm{en}$	0.7988	-
b_0	0.2547	-
$K_{\Theta\mathrm{d}}$	0.9170	-
c_1	2.723	W/(m^2K)
c_2	0.0147	W/($\mathrm{m}^2\mathrm{K}^2$)
c_3	0.1319	Ws/(m^3K)
c_4	-0.0755	-
c_5	7141.2	WS/(m^2K)
c_6	0.00576	s/m

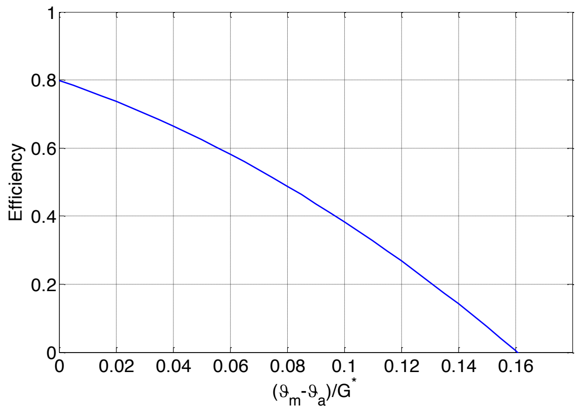
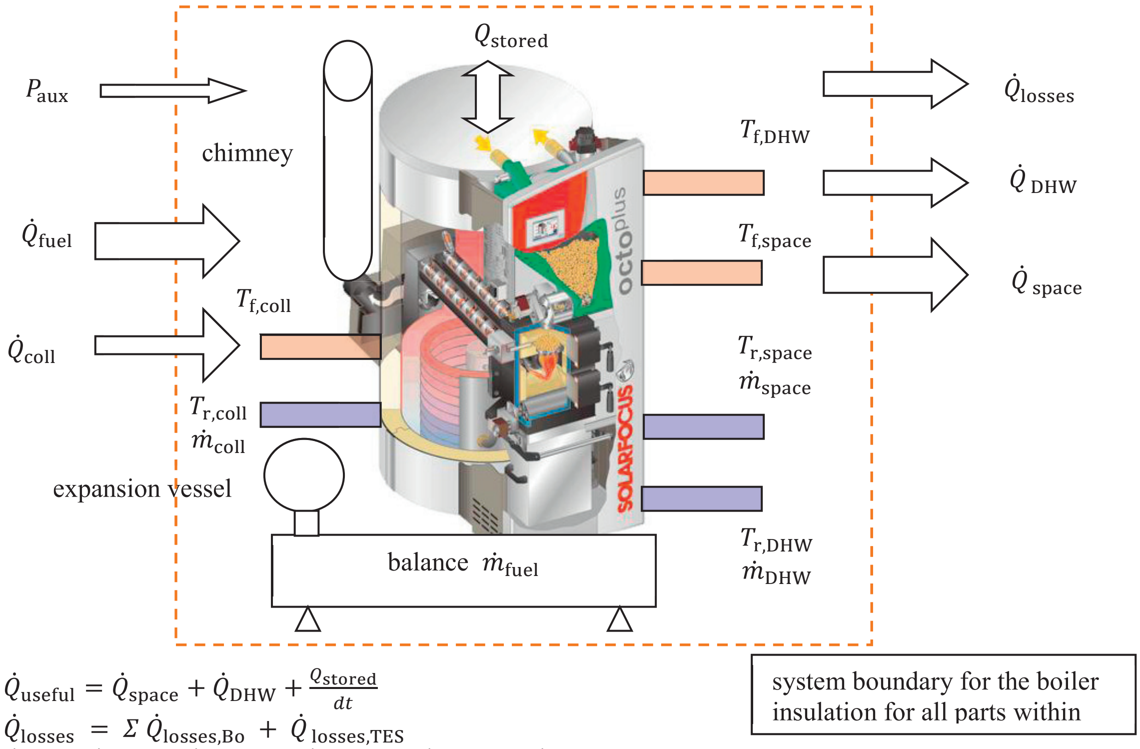


Fig. 1. Collector efficiency curve according to the parameters identified by the quasi-dynamic test method with regard to EN12975:2006 chapter 6.3 [1]

2.2. Wood pellet boiler

By measuring the pellet consumption, the consumed heat for space heating and domestic hot water and the losses, it was possible to make a full energy balance to calculate the system performance. The tested pellet boiler Octoplus from Solarfocus GmbH is directly integrated into the solar storage. Figure 2 shows a sectional view of the investigated storage integrated boiler. The down firing combustion technology boiler is equipped with a 500 l solar storage, a pellet tank and a storage integrated flue gas to water heat exchanger. The solar collector is directly connected to the storage with an internal coil heat exchanger. The power range of the investigated pellet boiler varies from 2.9 to 14.9 kW and the maximum flow temperature is 85 °C. The boiler was type tested according to [4] with a thermal efficiency of 93.1 % at full load and 89.4 % at standardized partial load. The laboratory test carried within this project are steady state measurements with a heating capacity of 30%, 50%, 75% and 95% and a return temperature of 20°C, 25°C, 30°C and 35°C according to [5] and transient tests for four characteristic days according to [6]. Figure 2 also depicts the heat transfer rates and the system boundary for the laboratory test set up. Complimentary information on the laboratory tests can be found in [7].



$$\dot{Q}_{useful} = \dot{Q}_{space} + \dot{Q}_{DHW} + \frac{Q_{stored}}{dt}$$
$$\dot{Q}_{losses} = \Sigma\, \dot{Q}_{losses,Bo} + \dot{Q}_{losses,TES}$$
$$\dot{Q}_{fuel} + \dot{Q}_{coll} = \dot{Q}_{losses} + \dot{Q}_{space} + \dot{Q}_{DHW} + \dot{Q}_{stored}$$

Fig. 2. Investigated storage integrated boiler; source: Solarfocus GmbH

3. Modeling and simulation

The combined wood pellet and solar thermal system was modeled in the simulation environment TRNSYS (Transient System Simulation). The boiler model (Type 869) was developed by Michel Haller [2] and extensively validated. The collector model (Type 832) was developed by Bengt Perers [3] and further improved by Michel Haller and also validated with experimental data. The thermal energy storage model (Type 340) was developed by Harald Drück [8] and validated with experimental data as well.

Since the boiler model was originally not developed for storage integrated boilers it has to be modified. The modification applied in this paper was suggested in the work of Michel Haller and is already validated [2].

The useful energy $\dot{Q}_{\mathrm{Bo}}$ from the boiler was transferred to the thermal energy storage with a fictive temperature $T_{\mathrm{dp,in}}$ of 89°C and a mass flow rate with regard to eq. (3). The mass flow rate through the boiler is set to 600 kg/h whenever the supply temperature is higher than the return temperature of the boiler.

$$\dot{m}_{\mathrm{Bo,ficitve}} = \frac{\dot{Q}_{\mathrm{Bo}}}{cp_{\mathrm{wat}}\,(T_{\mathrm{dp,in}} - T_{\mathrm{dp,out}})} \qquad (3)$$

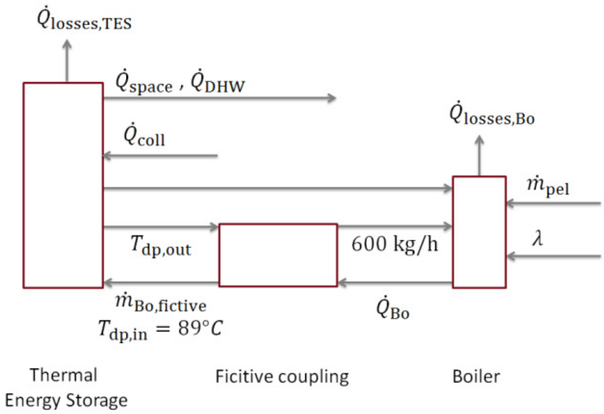


Fig. 3. Schematic of the fictive coupling of the pellet boiler and the thermal energy storage to simulate a storage integrated boiler according to [2]

The schematic of the simulation model is represented in fig. 3. The parameters of the boiler model and the thermal energy storage model were identified by applying an evolutionary optimization algorithm. The TRNOpt interface in TRNSYS was applied to connect the model to GenOpt [9] (Generic Optimization program). The laboratory test results were used to parameterize the boiler model under steady state conditions. Monitoring data of a realized plant under real operating conditions are used to parameterize the storage and the storage integrated heat exchanger. The identified parameters are listed in tab. 3.

Table 3. Parameters determined for the boiler model and the thermal storage model

Parameter	Value	Unit	Description
$C_{th,bo}$	200	kJ/K	Thermal capacity of the boiler associated only with the material of the combustion chamber without water
k_{eff}	29.91	kJ/(hmK)	Effective internal heat conduction of the thermal energy storage
UA_{bottom}	4.811	kJ/(hK)	Heat loss coefficient of the bottom of the thermal energy storage
UA_1	27.98	kJ/(hK)	Heat loss coefficient of the first zone of the thermal energy storage (lower quarter of the storage)
UA_2	15.08	kJ/(hK)	Heat loss coefficient of the second zone of the thermal energy storage
UA_3	12.66	kJ/(hK)	Heat loss coefficient of the third zone of the thermal energy storage
UA_4	0.537	kJ/(hK)	Heat loss coefficient of the fourth zone of the thermal energy storage (upper quarter of the storage)
UA_{top}	0.03985	kJ/(hK)	Heat loss coefficient of the top of the thermal energy storage
UA_{solar}	800	kJ/(hK)	Heat transfer coefficient of the storage integrated solar heat exchanger

The monitored plant is set up in a single family house with a necessary heating capacity of 14.9 kW. The three solar collectors are roof mounted and oriented to the south. To evaluate the performance of the overall system we defined three key figures with regard to eq. (4) to (6).

Thermal seasonal performance factor:

$$SPF_{\mathrm{th}} = \frac{\int (Q_{\mathrm{space}} + Q_{\mathrm{DHW}})dt}{\int Q_{\mathrm{pel}}dt} \tag{4}$$

Energy utilization ratio:

$$ER = \frac{\int (Q_{\mathrm{space}} + Q_{\mathrm{DHW}})dt}{\int (I_{\mathrm{solar}} + Q_{\mathrm{pel}})dt} \tag{5}$$

Solar fraction:

$$SF = \frac{\int Q_{\mathrm{coll}}dt}{\int (Q_{\mathrm{space}} + Q_{\mathrm{DHW}})dt} \tag{6}$$

The energy input from the wood pellets is calculated according to eq. (7):

$$\dot{Q}_{\mathrm{pel}} = \dot{m}_{\mathrm{pel}}\, NHV_{\mathrm{wb}} \tag{7}$$

The results of the key figures for the monitored system to evaluate the overall system performance are given in tab. 4 and compared to the simulation results for the same plant under the same boundary conditions. Since the monitoring started in November 2011 the results given in tab. 4 are only from 11

November 2011 until 24 May 2012. The monitoring is still continuing and will be extended to three additional plants.

Table 4. Results of the key figures for the monitored plant between 11 November 2011 and 24 May 2012, compared with the simulation under the same boundary conditions

Key figure	Monitoring	Simulation
SPF_{th}	0.828	0.822
ER	0.648	0.643
SF	0.336	0.339

4. Conclusion

Laboratory test results could be applied to successfully parameterize a simulation model of a storage integrated pellet boiler combined with solar collectors. A realized plant set up in a single family house has been measured from 11 November 2011 to 24 May 2012. The gathered data showed promising system performance for the combined system. The SPF_{th} of the monitored plant is as high as 82% for space heating and domestic hot water. Even though the monitoring data for the summer time has yet not been available, the solar fraction of around 34% is considerable high. However, the configuration of the integrated pellet boiler leads to the fact that the thermal losses of the thermal energy storage cannot be separated into losses caused by the solar collector or the pellet boiler. Thus the actual utilization of the solar energy stored cannot be quantified. Since the boiler efficiency ranges from more than 90% to 82% which is in the same range as the SPF_{th} it seems that most of the solar energy stored in the solar thermal storage could not efficiently been used, e.g. low temperature solar input.

The simulation results showed very good agreement with the monitored data under the same boundary conditions. In one of the next steps the simulation model will serve to investigate case studies of different system configurations, e.g. variation of storage volume and collector area, to further improve the system performance. Another focus of the numerical investigations will be the optimization of the control strategy, especially the set points for boiler on and off mode, to maximize the solar fraction of the overall system.

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